Irrig Sci (2003) 22: 95–104
DOI 10.1007/s00271-003-0074-6

ORIGINAL PAPER

**Douglas J. Hunsaker · Paul J. Pinter Jr.
Edward M. Barnes · Bruce A. Kimball**

Estimating cotton evapotranspiration crop coefficients with a multispectral vegetation index

Received: 12 December 2002 / Accepted: 13 June 2003 / Published online: 14 August 2003

Abstract Crop coefficients are a widely used and universally accepted method for estimating the crop evapotranspiration (ET_c) component in irrigation scheduling programs. However, uncertainties of generalized basal crop coefficient (K_{cb}) curves can contribute to ET_c estimates that are substantially different from actual ET_c. Limited research with corn has shown improvements to irrigation scheduling due to better water-use estimation and more appropriate timing of irrigations when K_{cb} estimates derived from remotely sensed multispectral vegetation indices (VIs) were incorporated into irrigation-scheduling algorithms. The purpose of this article was to develop and evaluate a K_{cb} estimation model based on observations of the normalized difference vegetation index (NDVI) for a full-season cotton grown in the desert southwestern USA. The K_{cb} data used in developing the relationship with NDVI were derived from back-calculations of the FAO-56 dual crop coefficient procedures using field data obtained during two cotton experiments conducted during 1990 and 1991 at a site in central Arizona. The estimation model consisted of two regression relations: a linear function of K_{cb} versus NDVI ($r^2=0.97$, $n=68$) used to estimate K_{cb} from early vegetative growth to effective full cover, and a multiple regression of K_{cb} as a function of NDVI and cumulative growing-degree-days (GDD) ($r^2=0.82$, $n=64$) used to estimate K_{cb} after effective full cover was attained. The NDVI for cotton at effective full cover was ~0.80; this value was used to mark the point at which the model transferred from the linear to the multiple regression function. An initial evaluation of the performance of the model was made by incorporating K_{cb} estimates, based on NDVI measurements and the developed regression functions, within the FAO-56 dual procedures and comparing the estimated ET_c with field observations from two cotton plots collected during an experiment in central Arizona in 1998. Preliminary results indicate that the ET_c based on the NDVI-K_{cb} model provided close estimates of actual ET_c.

Communicated by R. Evans

D. J. Hunsaker (✉) · P. J. Pinter Jr. · B. A. Kimball
US Water Conservation Laboratory, USDA-ARS,
4331 East Broadway Road, Phoenix, AZ 85040, USA
E-mail: dhunsaker@uswcl.ars.ag.gov
Tel.: +1-602-4371702
Fax: +1-602-4375291

E. M. Barnes
Cotton Incorporated,
6399 Weston Parkway, Cary, NC 27513, USA

Introduction

A fundamental requirement for accurate irrigation scheduling is the determination of actual crop evapotranspiration (ET_c) for each day during the growing period. A practical and extensively applied method for estimating ET_c is the crop coefficient (K_c) approach (Doorenbos and Pruitt 1977; Jensen and Allen 2000), in which an experimentally developed dimensionless K_c is multiplied by reference evapotranspiration (traditionally grass or alfalfa) to compute ET_c. Values of K_c determined for most agricultural crops will typically vary in relation to changes in vegetative growth until effective full cover is attained. After full cover, the K_c will tend to decline, the extent of which is primarily dependent on the particular growth characteristics of the crop (Jensen et al. 1990) and the irrigation management during the late season (Allen et al. 1998). A crop coefficient curve is the seasonal distribution of K_c, often expressed as a smooth continuous function in time or some other time-related index, such as thermal units (Jensen et al. 1990).

Increased soil evaporation can cause K_c values to deviate significantly from the empirically determined K_c function for several days following irrigation or heavy rainfall. To account for the effects of soil evaporation, the Food and Agriculture Organization (FAO) Irrigation and Drainage paper no. 56 (FAO-56), *Crop evapotranspiration* (Allen et al. 1998), presented dual crop coefficient procedures to allow computation of more precise estimates of daily ET_c for days following irrigation or rain. For the FAO-56 dual crop coefficient approach, the single K_c is separated into two coefficients, a basal crop coefficient, K_{cb} (primarily crop transpiration), and a wet soil evaporation coefficient, K_e, to quantify the individual contributions for the two components of ET_c. The dual procedures also include a water stress coefficient (K_s) to quantify the effects of soil water stress on ET_c. Several recent studies conducted in Texas and Arizona have shown that the FAO-56 dual crop coefficient procedures can provide good estimates of daily ET_c for fully-irrigated grain sorghum (Tolk and Howell 2001), cotton (Hunsaker 1999; Howell et al. 2002), and alfalfa (Hunsaker et al. 2003).

While the FAO-56 dual procedures provide an excellent framework for calculating daily ET_c, its successful application in providing reliable estimates for irrigation scheduling is highly dependent on the ability to construct a K_{cb} curve that matches the actual crop growth conditions that occur during a given season (Allen et al. 1998; Hunsaker et al. 2003). Because the K_{cb} curve functions described in FAO-56, and generally those used with most state-of-the-art irrigation-scheduling programs, are time-based, they lack the flexibility required to capture atypical crop development and water-use patterns caused by weather anomalies (Bausch and Neale 1989). Some improvements over time-based curves to account for the effects of climatic variability have been reported when K_{cb} curves were derived as a function of a thermal-based index, such as cumulative growing-degree-days (GDD) (Stegman 1988; Slack et al. 1996).

The K_{cb} curve is designed to reflect ET_c for optimum agronomic and water management conditions (Allen et al. 1998). However, K_{cb} curve adjustment to estimate ET_c when crop growth and water use deviate from "standard" conditions due to nutrient, crop density, pest, or other crop stress factors are not commonly nor easily implemented using conventional K_{cb} curves. Appropriate irrigation scheduling is also hindered by occurrences of spatially and temporally variable ET_c fluxes within a field or area created by a variety of factors, for example, non-uniform water application, soil water-holding characteristics, nutrient availability, stand density, and micro-climatic conditions. However, accounting for spatial and temporal variations in water use with present crop coefficient procedures is extremely difficult, if not impossible. Even for standard agronomic, water management, and weather conditions, and minimal crop variability, applying crop coefficient curves from the literature will usually require some form of locality adjustment, unless the curves were specifically developed for the particular location.

Remote sensing techniques offer a means of overcoming many of the shortcomings of conventional crop coefficient ET_c estimation by providing real-time feedback on daily crop water use as influenced by actual crop developmental patterns, local atmospheric conditions, and field spatial variability. Multispectral vegetation indices (VIs), computed as differences, ratios, or linear combinations of reflected light in the visible (blue, green, or red) and near infrared (NIR) spectra have been found to be closely related to several crop growth parameters (Heilman et al. 1982; Jackson and Huete 1992; Moran et al. 1995). The simple ratio (NIR/red) and the normalized difference vegetation index [NDVI = (NIR-red)/(NIR + red)] have gained wide acceptance for estimating plant cover, green plant biomass, and leaf area index. The potential to use multispectral VIs as near real-time surrogates for crop coefficients was proposed over two decades ago by Jackson et al. (1980), who pointed out the similarity between the seasonal pattern of a VI for wheat and that of the wheat crop coefficient. This VI-based crop coefficient concept was established by Bausch and Neale (1987) and Neale et al. (1989) who derived basal crop coefficients for corn in Colorado based on several VIs. Bausch and Neale (1989) and Bausch (1995) incorporated VI- based corn coefficients for use in existing scheduling algorithms and reported improvements in corn irrigation scheduling due to better estimation of water use and more appropriate timing of irrigations. Implementing VI-based crop coefficients within irrigation scheduling procedures could potentially be more successful and far-reaching than other remote sensing methods, because of the widespread familiarity and use of the crop coefficient methodology. In addition, VI data can be routinely measured either on the ground, in the air, or by satellite. Determining daily crop ET with the VI-based crop coefficient would require frequent, but not daily, VI measurements, since the smooth general shape of the K_{cb} curve over a growing season would allow data to be extrapolated over a period of up to a week. Only limited research has been conducted to expand the development of VI-based crop coefficients for crops other than corn, although simulation studies suggest that VIs could be used to obtain crop coefficients for several other important agricultural crops (Choudhury et al. 1994).

Cotton (*Gossypium hirsutum* L.) is one of several primary crops produced in the arid, desert regions of the southwestern USA. Cotton's high water-use requirement coupled with increasing costs for water in the region require cotton growers to implement irrigation practices that will lead to increased water-use efficiency. One of the most important elements will be a greater emphasis on proper irrigation scheduling. The focus of this article is to provide a means to improve cotton irrigation scheduling via real-time crop coefficient ET_c estimation.

Data on ET_c obtained for two cotton seasons during previous experiments in the southwestern USA were used to derive basal crop coefficient data using back-calculations of the FAO-56 dual crop coefficient procedures. The objectives were to develop a model based on the derived data for estimating K_{cb} for a full-season cotton crop as a function of the multispectral vegetation index, NDVI; and to provide an initial performance evaluation of the model based on field data for another full-season cotton cultivar grown in a different year.

Methods and materials

Data acquired during Free-Air CO_2 Enrichment (FACE) cotton experiments in 1990 and 1991 were used to derive cotton basal crop coefficients for developing an NDVI-based K_{cb} model. The FACE studies were conducted on production-scale cotton fields in central Arizona (Hendrey and Kimball 1994), during which data were collected for a wide range of plant, soil, and meteorological parameters. Information about the experimental procedures, and various descriptions on the methodology of data collection and interpretation, are provided in Mauney et al. (1994), Hunsaker et al. (1994), and Pinter et al. (1994, 1996).

The broad objective for the FACE experiments was to study the interactive effects of elevated CO_2 and irrigation water supply on cotton. Experimental treatments included cotton grown under both ambient CO_2 (control treatment) and at concentrations about 45% higher than ambient (FACE treatment) with ample (wet treatment) and limited (dry treatment) water application. However, the data used in the derivation of the cotton basal crop coefficients excluded treatments exposed to either elevated CO_2 or limited water application. Therefore, only the control–wet (CW) treatment data were used. Brief descriptions of the experimental methodology and specific measurements pertinent to the present study follow.

Crop culture

Experiments were conducted during 1990 and 1991 on a 9-ha field at the University of Arizona, Maricopa Agricultural Center (MAC). A full-season, short-staple cotton (*Gossypium hirsutum* L., cv. Deltapine 77), well-adapted to central Arizona climatic conditions, was seeded during mid- to late April in east–west rows on raised soil beds, spaced 1.02 m apart. After emergence, the population was thinned to 10 plants m^{-2}. Cultivation, insect and weed control, and nutrient application were managed according to recommendations of the Arizona State Extension Service and University of Arizona research and support staff. Cotton was supplied with an average of 142 kg ha^{-1} N during each year (Pinter et al. 1996). Irrigation was terminated and seed cotton was harvested in mid-September of each year.

Soil characteristics

The soil at the FACE experimental site is classified as a Trix clay loam [fine-loamy, mixed (calcareous), hyperthermic Typic Torrifluvents]. Volumetric soil water contents for the top 0.7 m of the soil profile average 30 and 20% at soil matric potentials of −33 and −1,500 kPa, respectively, whereas the corresponding water contents for the subsurface profile (0.7–2.0 m) average 22 and 12%, respectively (Hunsaker et al. 1994).

Irrigation management

Irrigation water was supplied with a subsurface drip irrigation system that included a single micro-tube line per 1.02-m row, buried 0.18–0.25 m below the soil surface. Irrigation timing and amounts for "wet" irrigation treatments were determined using estimates of cotton ET_c based on cotton crop coefficients multiplied by reference evapotranspiration (Mauney et al. 1994). Three days after planting, 290 and 270 mm of water was applied to all treatments for seed germination in 1990 and 1991, respectively (Hunsaker et al. 1994). Cumulative amounts of the metered irrigation applications from planting through harvest averaged 1,180 and 1,030 mm for the CW treatments of 1990 and 1991, respectively, and seasonal rainfall was 125 and 41 mm in 1990 and 1991, respectively (Hunsaker et al. 1994).

Crop height and leaf area index measurements

Cotton canopy height (h_c) and leaf area index (LAI) were measured at 7- to 14-day intervals during the growing season (Mauney et al. 1994). Thirteen measurements were made in 1990 and 16 in 1991.

Evapotranspiration from soil water balance

Soil water contents were measured at two locations in each plot with neutron-scattering equipment at 7- to 14-day intervals during the two cotton growing seasons (Hunsaker et al. 1994). Measurements were made during early morning hours. Residuals calculated from the soil water-balance equation (Jensen et al. 1990) were used to determine the cumulative cotton ET_c that occurred between successive soil water content measurements, assuming negligible drainage below the crop root zone.

Meteorological data and reference evapotranspiration (ET_o)

Meteorological data were provided by an AZMET weather station (Brown 1989) located on a well-watered grass site at MAC ~2 km from the field site. Daily AZMET data for solar radiation, air temperature, wind speed, and humidity were used to calculate daily grass-reference evapotranspiration (ET_o) using the FAO Penman–Monteith method [equation 6 in FAO-56 (Allen et al. 1998)]. The AZMET weather station also provided information on daily cotton heat units, or growing-degree-days (GDD), which were calculated by the sine curve method using upper and lower air temperature thresholds of 30 and 12.8°C, respectively, as described by Brown (1991).

Canopy reflectance and transmittance

Crop canopy reflectance factors were measured two to four times a week during the growing seasons (Pinter et al. 1994). In 1990, 44 sets of canopy reflectance measurements were made between 30 April and 18 September, and in 1991, 70 sets of measurements were made between 19 April and 15 September. Observations were made for all plots using a hand-held, four-band radiometer equipped with 15° field-of-view optics and spectral bandpass spanning three visible (blue, green, and red) and one NIR wavelength intervals. Data were collected at a morning time period corresponding to a nominal solar zenith angle of 45°. The NDVI was computed from reflectance factors in near infrared (0.79–0.89 μm) and red (0.61–0.68 μm) wavebands as: NDVI = (NIR-red)/(NIR + red).

Pinter et al. (1994) also described measurements of the incident, transmitted, and reflected components of the radiation balance using a single, hand-held, line quantum sensor. They computed the fraction of the photosynthetically active radiation (PAR) absorbed by the canopy (fA_{PAR}) from a light balance equation using the measured fractions of PAR transmitted through the canopy (fT_{PAR}), reflected from the canopy, and reflected from the soil. The data were obtained on three dates in 1990 and seven dates in 1991 for all plots. In both years, the initial line quantum sensor measurements were begun 49 days after crop emergence.

Basal crop coefficient derivation: general methodology

The FAO-56 dual crop coefficient approach (Allen et al. 1998) describes the relationship between ET_c and ET_o by separating the single K_c into the basal crop and soil water evaporation coefficients:

$$K_c = (K_{cb} + K_e) = ET_c/ET_o \qquad (1)$$

where ET_c and ET_o are in mm day^{-1}.

The basal crop coefficient, K_{cb}, represents the ratio of ET_c/ET_o for conditions when, first, the soil surface layer is dry (i.e., when $K_e = 0$) and, second, the soil water within the root zone is adequate to sustain full plant transpiration (non-stressed conditions). The soil evaporation coefficient, K_e, describes the contribution of the evaporation component of ET_c when the soil surface is wetted following irrigation or rain (Allen et al. 1998). When the available soil water of the root zone drops below a critical level, crop water stress can occur and reduce ET_c. In the FAO-56 dual procedures, the effects of water stress on ET_c can be estimated by multiplying K_{cb} by the water stress coefficient (K_s):

$$K_{cb}K_s + K_e = ET_c/ET_o \qquad (2)$$

where $K_s < 1$ when the available soil water is insufficient for full ET_c, and $K_s = 1$ when there is no soil water limitation on ET_c.

Soil water-balance determinations of cotton cumulative ET_c for 7- to 14-day intervals during the cotton growing seasons were applied in back-calculations of the FAO-56 dual crop coefficient procedures to derive daily K_{cb} data for the entire growing season. The approach was similar to back-calculations of the FAO-56 procedures for deriving alfalfa K_{cb} from ET_c measurements (Hunsaker et al. 2003). The K_{cb} data were derived separately for each of the four control–wet replicates in both the 1990 and 1991 FACE experiments. Cumulative ET_c determinations for each measurement interval during the 1990 season are shown for replicate 1 of the CW treatment in Fig. 1a, along with the cumulative ET_o for each interval.

For each replicate, daily time-step calculations for K_{cb}, K_e, K_s, ET_c, ET_o, and other parameters (described later) required in the FAO-56 dual crop coefficient procedures were made within a spreadsheet that contained all the computations for each day of the growing season. The days for the growing season were then partitioned into a series of successive time intervals, whose lengths (7 to 14 days) were established by the number of days between two successive soil water content measurements. For each 7- to 14-day interval, the cumulative ET_c for the interval was known from soil water-balance measurements and the daily ET_o for each day in the interval was calculated from the FAO Penman–Monteith equation using daily weather data. Thus, for a given interval, the daily values for K_{cb}, K_e, and K_s were determined as a consequence of the known values for cumulative ET_c, daily ET_o, and other parameter estimates, using back-calculations of the dual crop coefficient calculations. This can be described mathematically for a given interval from day 1 to day $n-1$, as:

$$ET_{c,i} = (K_{cb,i}K_{s,i} + K_{e,i})ET_{o,i} \qquad (3)$$

where day 1 is the day a soil water content measurement was made, and day n is the next day a soil water content measurement was made; the summation of $ET_{c,i}$ from day 1 to day $n-1$ equals the cumulative ET_c for the interval; $K_{cb,i}$, $K_{s,i}$, and $K_{e,i}$ are the basal crop, water stress, and soil evaporation coefficients on day i, respectively; and $ET_{o,i}$ is the grass-reference evapotranspiration on day i.

Derivation involved adjusting the $K_{cb,i}$ values for the given measurement interval until the right-hand side of Eq. 3 matched the quantity on the left-hand side of the equation, i.e., the actual cumulative ET_c that was determined for the interval. However, for each measurement interval, the $K_{cb,i}$ values were forced to either increase or decrease linearly along the same slope from the first to the last day of the interval, with K_{cb} magnitude dependent upon the value for the $K_{cb,i}$ determined on the last day of the previous measurement interval. This is illustrated with the $K_{cb,i}$ data derived for replicate 1 of the CW treatment in 1990 (Fig. 1b), which shows that the $K_{cb,i}$ for this replicate increased from interval to interval (positive slopes) during the first half of the growing season, and typically decreased (negative slopes) during the second half of the season.

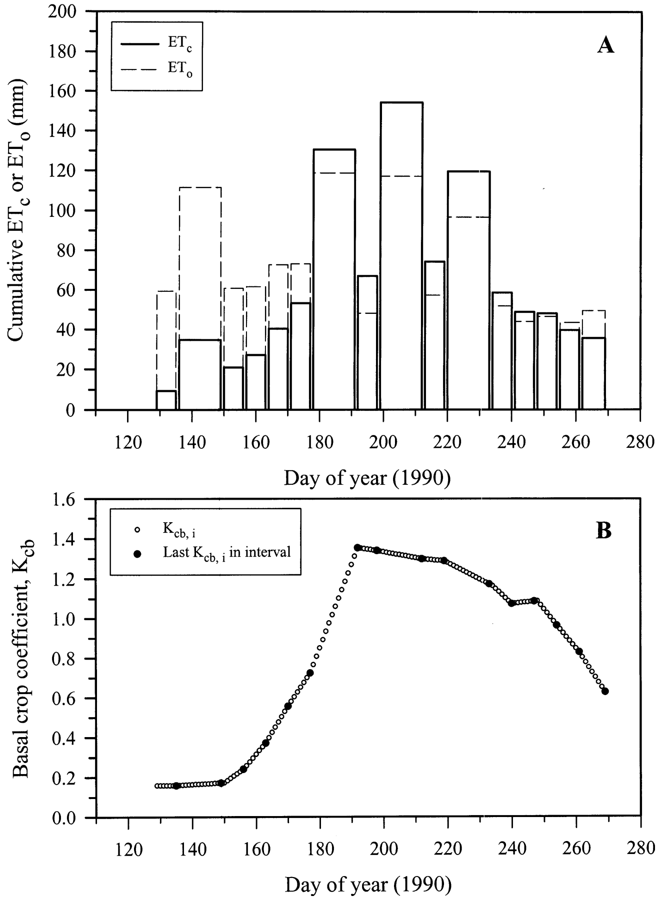


Fig. 1 a Cumulative ET_c determinations for 7–14 day measurement intervals for replicate 1 of the control–wet (*CW*) treatment during the 1990 FACE experiment, along with the calculated cumulative ET_o for each interval; **b** derived daily K_{cb} with indication of the daily K_{cb} value at the end of each measurement interval

Calculation of K_e

The FAO-56 dual crop coefficient calculations were used to estimate the separate contribution to ET_c, apart from basal crop water use, due to soil evaporation (described by K_e) following surface soil wetting from irrigation and rainfall. Daily values for K_e are determined using a daily soil water-balance computation of the surface soil evaporation layer (Z_e) subject to drying by evaporation. Soil parameters required to determine daily K_e include the field capacity (FC) and permanent wilting point (PWP) of the surface soil layer, the readily evaporable water (REW), and the depth of Z_e. The same soil parameters were used for all replicates in both years. The FC and PWP were taken as the site-average volumetric soil water contents in the upper profile at soil matric potentials of −33 and −1,500 kPa, respectively. A typical REW value for a loam soil of 10 mm (FAO-56, table 19) and a surface soil evaporation layer, Z_e, of 0.125 m were used in the calculations. The total evaporable water (TEW) of the soil surface layer, calculated using FAO-56, equation 73, was 25 mm. Daily values for crop height, h_c, used in the FAO-56 K_e calculations, were estimated by linear interpolation of the measured crop heights, as illustrated in Fig. 2a for replicate 1 of the CW treatment of 1990.

Two final parameters are required for determining K_e: (1) the daily fraction of the soil surface shaded by the canopy (f_c), or conversely the unshaded fraction ($1-f_c$), and (2) the fraction of the soil surface wetted (f_w) during each irrigation and precipitation event. Values for the unshaded fraction of the canopy, $1-f_c$, were

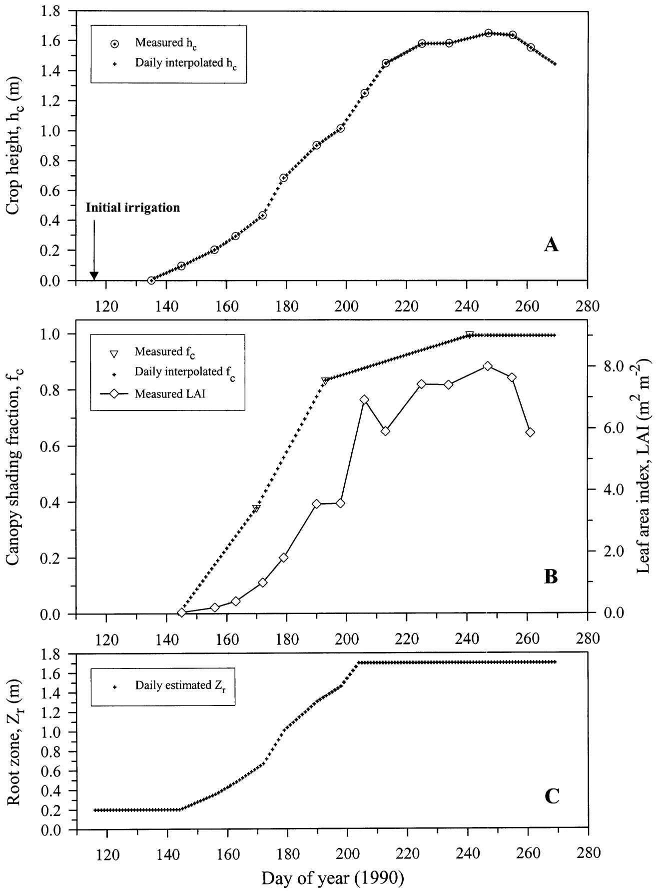


Fig. 2 For replicate 1 of the CW treatment, 1990 FACE experiment: **a** measured and interpolated crop height (h_c); **b** measured and interpolated canopy shading fraction (f_c) and measured leaf area index (*LAI*); **c** estimated depth of daily root zone (Z_r)

approximated from the fraction of the incident PAR transmitted through the canopy, as determined from line quantum sensor measurements. Daily values for fT_{PAR} ($\approx 1 - f_c$) were estimated by linear interpolation between days of measurement. The interpolated measured data for canopy shading fraction (f_c) and measured LAI data followed similar trends throughout the growing season (Fig. 2b). For both years and all replicates, a value of 1.0 was assigned for f_w when rain occurred (i.e., the entire soil surface was assumed to have been wetted). Following subsurface drip irrigation events, the value used for f_w was calculated using the FAO-56 recommendations for subsurface drip systems as follows:

$$f_w = 0.30(1 - 0.67 f_c) \tag{4}$$

Calculation of K_s

A daily soil water balance of the active root zone (separate from the surface soil evaporation layer soil water balance) is needed in the FAO-56 calculations to determine the daily water stress coefficient, K_s, and thereby any reduction for daily ET_c due to soil water stress. The root zone water-balance equation (FAO-56, equation 85) expresses soil water contents in terms of root zone depletion (D_r). Thus, D_r is viewed as the depth of water required to refill the root zone to field capacity. The root zone water balance for an interval from day i to day $i+1$ is written as:

$$D_{r,i+1} = D_{r,i} + R_i + I_i - ET_{c,i} - DP_i \tag{5}$$

where

$D_{r,i}$ root zone depletion at the beginning of day i (mm),
$D_{r,i+1}$ root zone depletion at the beginning of the next day $i+1$ (mm),
R_i rainfall during day i (mm),
I_i irrigation depth during day i (mm),
$ET_{c,i}$ crop evapotranspiration for day i (mm),
DP_i deep percolation out of the root zone on day i (mm)

The FAO-56 root zone water balance limits the minimum value of D_r to zero (i.e., field capacity). In the absence of irrigation or rainfall, calculation of equation 5 results in an increase in the root zone depletion at the beginning of day $i+1$ due to $ET_{c,i}$. Following irrigation or rain on day i, the root zone water balance (when assuming deep percolation is zero) may calculate an increase in $D_{r,i+1}$ that exceeds FC (i.e., results in a negative value for $D_{r,i+1}$). When this occurred, the total amount of water above field capacity on day $i+1$ was assumed to have been lost to deep percolation on day i, following any ET_c for day i.

In the FAO-56 procedures, K_s is described as a function of the total available water (TAW) within the root zone, the readily available water (RAW) within the root zone, and D_r, as determined from the root zone water balance. For a given day i, the calculation of K_s is given as:

$$K_{s,i} = (TAW_i - D_{r,i})/(TAW_i - RAW_i) \tag{6}$$

where $K_{s,i} = 1$ when $D_{r,i}$ is smaller than or equal to RAW_i, and $K_s < 1$ otherwise. For a given day, TAW_i is determined from the daily crop rooting depth ($Z_{r,i}$) and the FC and PWP for soil at the rooting depth. The RAW_i is then expressed as $pTAW_i$, where p is the soil depletion factor that represents the fraction of TAW_i that can be depleted from the root zone before water-stress occurs.

In computing daily K_s with Eq. 6, it was assumed that the daily Z_r for all replicates of both years increased from a minimum value of 0.20 m for the first 30 days of the season to a maximum of 1.7 m at mid-season (Allen et al. 1998), and that the development of Z_r increased in proportion to the increase in the measured and interpolated crop height. As shown for replicate 1 of the CW treatment in 1990, the maximum Z_r (Fig. 2c) was presumed to be reached when crop height had increased to 1.2 m on day of year (DOY) 204 (Fig. 2a).

The recommended p value for cotton when ET_c is 5 mm day^{-1} is 0.65 (FAO-56, table 22). Following FAO-56 procedures, p was adjusted when ET_c differed from 5 mm day^{-1} by the FAO-56 numerical approximation:

$$p_i = 0.65 + 0.04(5 - ET_{c,i}) \tag{7}$$

where p_i is the soil depletion fraction on day i, limited to $0.1 \leq p_i \leq 0.8$, and $ET_{c,i}$ is the cotton ET_c on day i, in mm day^{-1}.

Example of back-calculations and K_{cb} derivation

Daily K_{cb} values derived using the FAO-56 back-calculations are illustrated for a 14-day measurement period (DOY 178–191) for replicate 1 in 1990 (Fig. 3). The measured cumulative ET_c was 131 mm and the cumulative ET_o was 119 mm from DOY 178–191. Root zone water-balance computations (Eq. 5) for each day of the interval began with the measured D_r made at the beginning of DOY 178 (shown as an enclosed circle in Fig. 3a). The open circles are the computed D_r at the beginning of each subsequent day in the interval, as determined after the appropriate irrigation and rain additions and ET_c subtractions are calculated from the root zone water balance for the previous day. For this example, and for the vast majority of intervals, daily root zone water-balance calculations suggested that no water was lost to deep percolation during the interval.

For K_{cb} derivation, the daily root zone computations for each measurement interval are forced to satisfy the condition that the computed and measured D_r be identical at the beginning of the next measurement interval (which occurred on DOY 192 for this

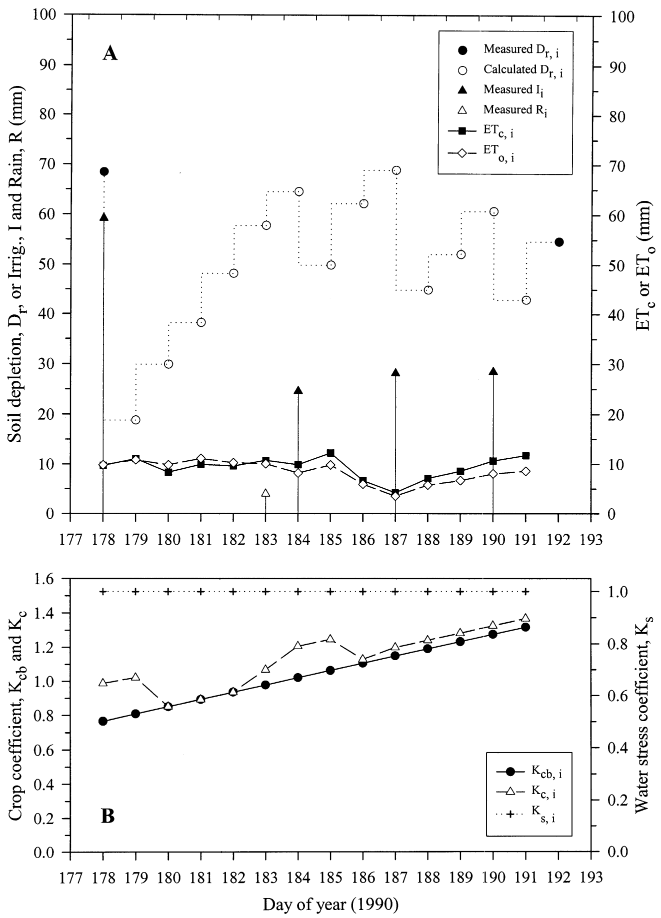


Fig. 3 For replicate 1 of the CW treatment, 1990 FACE experiment: **a** daily root zone water balance (Eq. 5) components for the measurement interval from DOY 178 to DOY 191 showing measured and calculated daily root zone depletion ($D_{r,i}$), daily measured irrigation (I_i) and rainfall (R_i), daily estimated evapotranspiration (ET_c), and calculated reference evapotranspiration (ET_o); **b** estimated daily basal crop coefficient ($K_{cb,i}$), estimated total daily crop coefficient ($K_{c,i}$), and estimated daily water stress coefficient ($K_{s,i}$) for days in the measurement interval

example). This condition implies that the summation of the computed daily ET_c from Eq. 3 (dependent upon daily K_{cb}) be identical to the measured cumulative ET_c for the interval. As the daily K_{cb} curve for the interval is adjusted, FAO-56 procedures calculate new estimates for daily ET_c, and the daily root zone computations are accordingly updated. Computations for the interval end when adjustment results in derived daily K_{cb} data that satisfy the root zone water-balance condition.

For the example interval, the daily root zone depletion computations applied in FAO-56 procedures indicated that water stress did not occur ($K_s = 1$) for any day (Fig. 3b). The difference between the K_c and K_{cb} value for a given day describes the magnitude for K_e, and thus the estimated contribution of soil evaporation for ET_c on the day. The daily K_e were increased following irrigation and rain, but the magnitudes for K_e decreased as K_{cb} (as well as canopy shading) increased during the interval (Fig. 3b).

Paired NDVI observations with derived K_{cb}

The measured NDVI for each control–wet replicate were interpolated linearly, generating daily NDVI values for the entire season. For each replicate, the average daily NDVI was calculated for each 7- to 14-day measurement interval during the season. The average

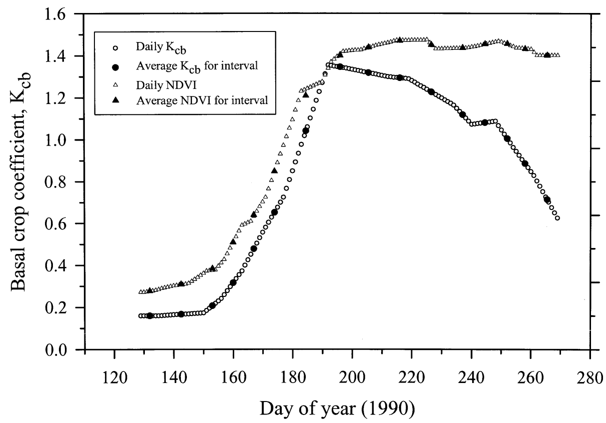


Fig. 4 Daily K_{cb} and normalized-difference vegetation index (*NDVI*) for replicate 1 of the CW treatment, 1990 FACE experiment, with indication of the average K_{cb} and NDVI (data pairs) as referenced by the mid-day for each of the measurement intervals

daily values were then paired with derived average daily K_{cb} values obtained for the corresponding replicate and measurement interval. The time-reference for the paired NDVI-K_{cb} data was taken as the middle day of the particular measurement interval. An example of the interval NDVI and K_{cb} data pairs obtained for replicate 1 of the CW treatment in 1990 is shown (Fig. 4). Regression procedures were used to model the NDVI-K_{cb} relationship using data for all replicates and both years.

Evaluation data

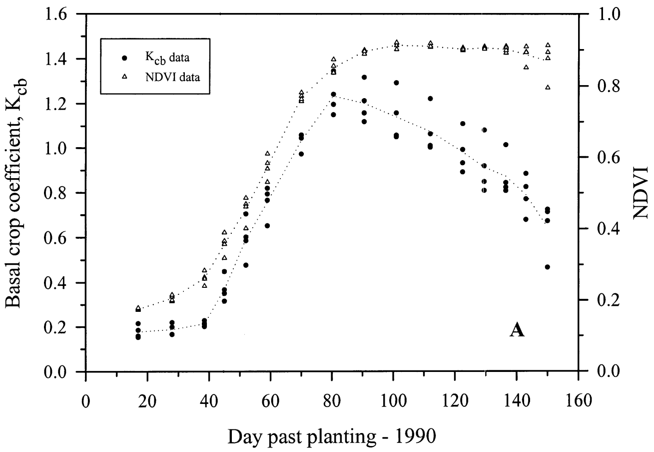
The NDVI-K_{cb} model was evaluated using data for another full-season cotton cultivar (*Gossypium hirsutum* L., cv. Deltapine 90) grown in another year, 1998, on a 1.3-ha sandy loam site at MAC. As described by Colaizzi et al. (2003), the experiment, initiated in late April 1998, consisted of two nitrogen levels with 16 treatment plots, with each plot ~22×22 m in size. The cotton was surface irrigated, and grown in the same row orientation (east–west) as the cotton in the FACE experiments. Soil water-content measurements using neutron probe and time domain reflectometry (Colaizzi et al. 2003) were begun in late May 1998. Supporting measurements collected during the experiment included canopy reflectances (NDVI) taken three times per week for each plot using a hand-held radiometer and, on a weekly basis, biomass, leaf area, plant height, and percentage canopy cover.

Two particular treatment plots (ample-N treatment) from the 1998 experiment that were described by Colaizzi et al. (2003) were used in this study for evaluating the NDVI-based model. Soil water-content data for each plot were used to calculate the cumulative ET_c for measurement intervals during the growing season, as was done for the FACE cotton replicates. Next, daily K_{cb} for the plots were derived using the previously described back-calculations of the FAO-56 dual procedures. Finally, estimated ET_c was calculated using the FAO-56 procedures with daily K_{cb} values generated from the model regression equations and measured NDVI data. Measured crop and soil parameters for the 1998 plots and local AZMET weather station data were used in the K_{cb} back-calculations and FAO-56 ET_c estimation procedures.

Results and discussion

NDVI-K_{cb} model

Values for K_{cb} and NDVI plotted versus days past planting reveal that both parameters increased in a



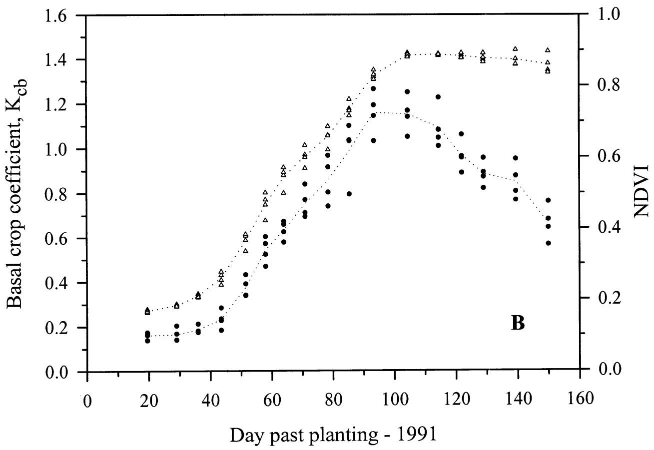


Fig. 5 Paired K_{cb} and normalized-difference vegetation index (*NDVI*) data with days past planting for all four replicates of control–wet treatment for **a** the 1990 and **b** the 1991 FACE experiments

similar manner from early crop development until a maximum K_{cb} was attained (Fig. 5a, b). For both years, maximum K_{cb} occurred at just about the time of effective canopy closure, when NDVI values for replicates were on the order of 0.80 or above, ˜81 and 94 days after planting for the 1990 (Fig. 5a) and 1991 (Fig. 5b) cotton-growing seasons, respectively. After effective full cover, NDVI vacillated within only a narrow range between 0.85 and 0.92 until about 140 days past planting. Thereafter, the NDVI for some replicates decreased below 0.85, indicating the beginning of crop senescence. Unlike the horizontal trend which occurred for NDVI after full cover, values for K_{cb} began to decrease with time once maximum K_{cb} had been attained. Consequently, to adequately describe the change in K_{cb} during the entire growing season, the NDVI-based K_{cb} model was developed using two separate regression functions that intersect approximately when effective full cover is reached.

The first relationship (open circles in Fig. 6) is a linear regression function that describes the increase in K_{cb} with NDVI from initial crop growth (NDVI$\approx$0.15) through the beginning of full cover, using an upper

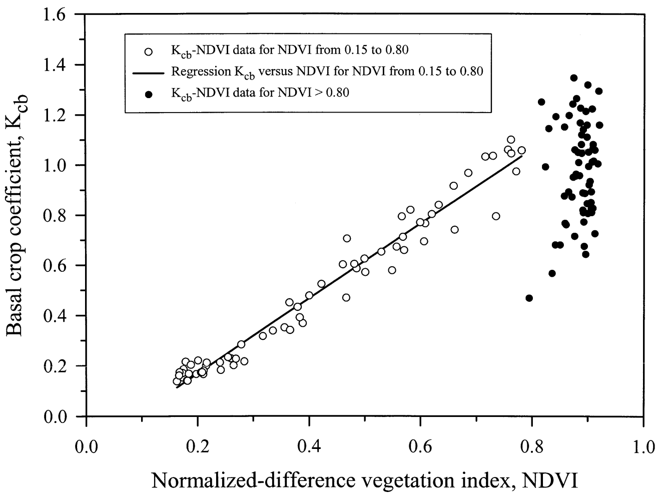


Fig. 6 Plotted K_{cb} versus normalized-difference vegetation index (*NDVI*) for K_{cb}-NDVI data pairs from all four replicates of the CW treatments of 1990 and 1991, and linear regression line for K_{cb} as a function of NDVI. Data pairs for NDVI greater than 0.80 were excluded from the regression

bound of 0.80 for NDVI. Linear regression of K_{cb} with NDVI using data for all replicates and both years resulted in an r^2 of 0.97, with minimal scatter around the regression line. Resultant regression coefficients and statistics are presented in Table 1. The K_{cb}-NDVI pairs shown when the NDVI increased above 0.80 (closed circles in Fig. 6) illustrate the deviation of the data from the linear function shortly after effective full cover was attained.

The pronounced downward trend for K_{cb} with minimal corresponding decreases for NDVI after full cover suggested that a time-dependency parameter added within the NDVI index would significantly improve K_{cb} estimation during the latter part of the growing season. Although several regression function forms and time-based indices were considered, a simple multiple linear regression function (Table 1) with cumulative GDD for the time index and NDVI for the crop growth index was selected for modeling the observed K_{cb} after full canopy was attained (Fig. 7a). For this relationship, growing-degree-days were accumulated, starting on the day NDVI reached 0.80 for a given replicate. Assuming constant NDVI values of 0.85 and 0.90 after full cover, K_{cb} generated with the multiple regression function illustrate how a relatively small difference in NDVI would affect the estimated magnitude of K_{cb} during the latter part of the growing season (Fig. 7b).

Evaluation of NDVI-based K_{cb} model

Evaluation of the NDVI-based K_{cb} model was made using data for two plots within the ample-N treatment of the 1998 cotton field experiment (Colaizzi et al. 2003). The derived daily K_{cb} for the replicates are compared with daily K_{cb} estimated from the model

Table 1 Regression coefficients and statistics relating cotton K_{cb} to normalized-difference vegetation index (NDVI) and cumulative growing-degree-days (GDD)

Growth stage	NDVI range	Regression coefficients			Regression statistics[a]		
		NDVI	Cumulative GDD[b]	Intercept	r^2	SE (K_{cb})	n
Early vegetative to effective full cover	0.15 to 0.80	1.49	na	−0.12	0.97	0.06	68
After effective full cover	>0.80	2.80	-5.69×10^{-4}	−1.17	0.82	0.09	64

[a] r^2 is the coefficient of determination, SE (K_{cb}) is the standard error of the K_{cb} estimates, and n is the number of data points
[b] Accumulation of GDD start when NDVI = 0.80. Note GDD are calculated by the sine curve method using upper and lower temperature thresholds of 30 and 12.8°C, respectively

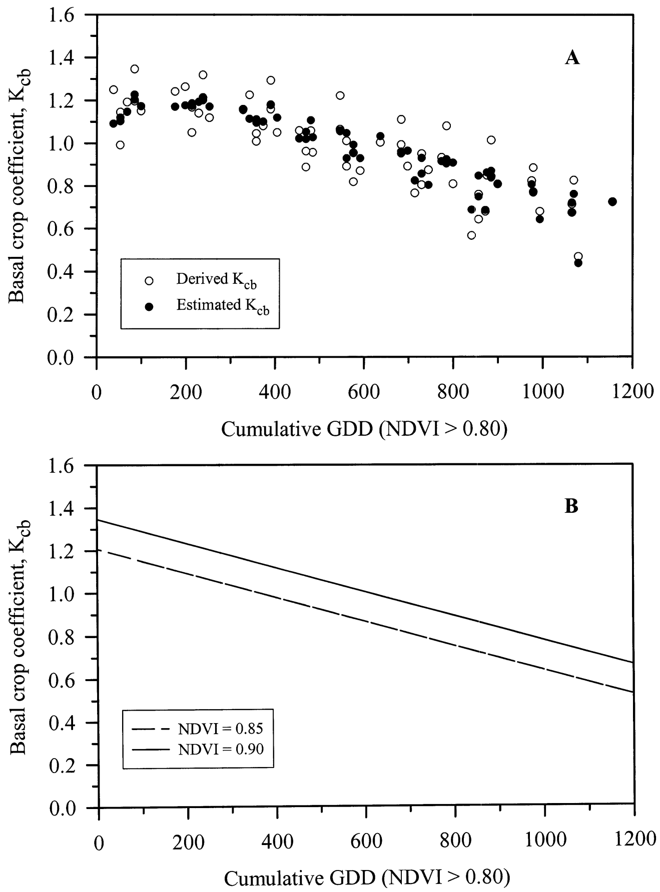


Fig. 7 a One-dimensional plot of K_{cb} data for CW replicates of 1990 and 1991, when the corresponding normalized-difference vegetation index (*NDVI*) was greater than 0.80, shown as a function of cumulative growing-degree-days (*GDD*), and estimates for K_{cb} calculated as a function of NDVI and cumulative GDD using the multiple regression function given in Table 1; **b** hypothetical K_{cb} lines calculated from the multiple regression function versus cumulative GDD when assuming constant values of 0.85 and 0.90 for NDVI. Note that the accumulation of growing-degree-days begin when the NDVI first reaches 0.80

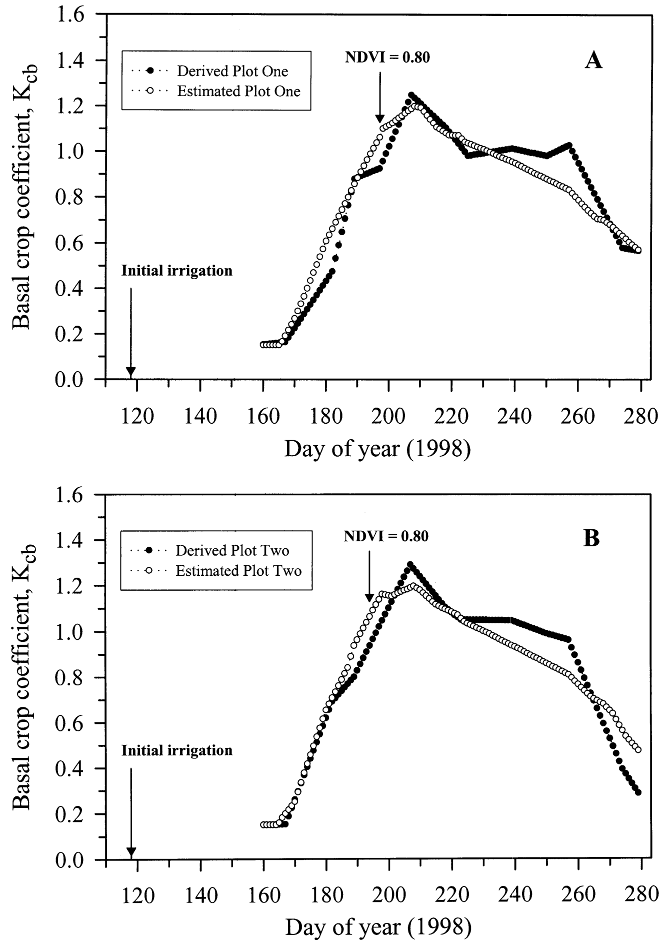


Fig. 8 Comparison of derived daily K_{cb} based on soil water-content measurements and back-calculations of the FAO-56 procedures with estimated daily K_{cb} based on NDVI measurements and the regression functions of Table 1 for **a** plot 1 and **b** plot 2 of the 1998 cotton experiment

regression functions based on NDVI measurements (Fig. 8a, b). Note that the time NDVI first reached 0.80 (≈effective full cover) for each plot is indicated in the figures, and marks the point at which the calibration transferred from the linear to the multiple regression function. Prior to NDVI reaching 0.80, there was a tendency for the linear model to overestimate derived K_{cb}, although agreement between estimated and derived K_{cb} was excellent for plot 2 through DOY 185. For both plots, the K_{cb} agreement was reasonably good during mid-season, i.e., from DOY 200 through DOY 230. However, the modeled K_{cb} based on NDVI underestimated derived K_{cb} during the following 30 days (DOY 230–260). The slower decline for the derived K_{cb} during that period in 1998 relative to the estimated NDVI-based K_{cb} may have resulted from an increase in the irrigation frequency to the 1998 plots starting on DOY 236 following installation and testing of a linear move irrigation system.

Cumulative ET_c estimated using the NDVI-based daily K_{cb} and FAO-56 dual crop coefficient procedures for the two plots of 1998 was in good agreement with observed cumulative ET_c based on soil water content data, as shown for 12 measurement periods occurring between DOY 160 and DOY 279 (Fig. 9a, b). As expected from the K_{cb} curves, the tendency was towards higher estimated ET_c than observed during the first half of the season prior to effective full cover, followed by lower estimated ET_c than observed for the latter half of the season. Considering all measurement periods for the first half of the season (DOY 160–207), estimated cumulative ET_c was 25 mm (9%) and 15 mm (5%) more than that observed for plots 1 and 2, respectively. For measurement periods from DOY 208 to DOY 279, estimated cumulative ET_c was 19 mm (4%) and 15 mm (4%) less than that observed for plots 1 and 2, respectively. Consequently, total estimated ET_c for all 12 measurement intervals differed from the observed by only +6 mm and 0 mm for plots 1 and 2, respectively.

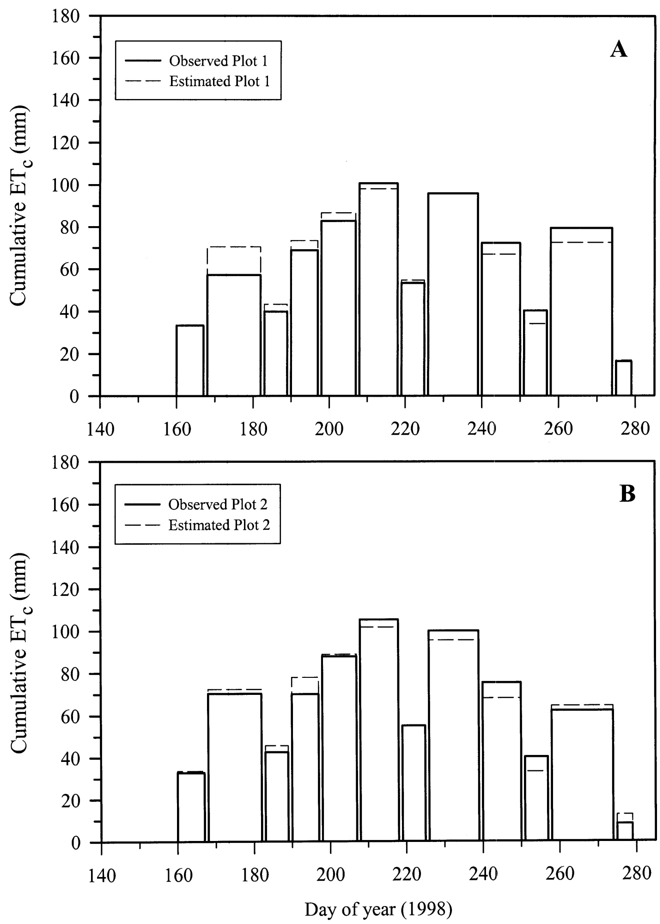


Fig. 9 Comparison of observed cumulative ET_c based on soil water-content measurements and estimated cumulative ET_c based on the modeled NDVI-based daily K_{cb} and FAO-56 dual crop coefficient calculations for **a** plot 1 and **b** plot 2 of the 1998 cotton experiment

Conclusions

Regression equations were developed to estimate the seasonal distribution of K_{cb} with the normalized-difference vegetation index for a full-season cotton cultivar grown in the southwestern USA. An initial evaluation of the model indicated that the NDVI-based K_{cb} provided ET_c estimations that closely described the observed ET_c attained for another cotton cultivar grown under different conditions than those under which the model was developed. The NDVI-based K_{cb} functions can be easily incorporated within the FAO-56 dual crop coefficient procedures and, thereby, provide a means to apply remotely sensed observations for real-time cotton irrigation scheduling. Additional experiments are currently being conducted in central Arizona to evaluate the NDVI-based K_{cb} application for use in scheduling irrigations for cotton. One area that will be addressed is the potential use of alternate vegetation indices or enhanced NDVI formulations to more readily track K_{cb} following canopy closure. Some of the primary benefits envisioned for using real-time multispectral-based K_{cb} in place of conventional K_{cb} curves include eliminating the need to hypothesize the time-scale for crop developmental stages and future weather conditions for a given cropping season. Because remotely sensed K_{cb} are expected to track the unique developmental patterns of the crop, field observation requirements, assumptions, and cumbersome procedures associated with adjusting conventional K_{cb} curves for conditions other than optimum could be eliminated as well. The remote sensing technique may also potentially provide the ability to detect and quantify differences in ET_c within a single field and on a field-by-field basis; information that at present is extremely difficult to obtain without labor-intensive methods.

References

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration. (FAO irrigation and drainage paper 56) Food and Agricultural Organization of the United Nations, Rome

Bausch WC (1995) Remote sensing of crop coefficients for improving the irrigation scheduling of corn. Agric Water Manage 27:55–68

Bausch WC, Neale CMU (1987) Crop coefficients derived from reflected canopy radiation: a concept. Trans ASAE 30(3):703–709

Bausch WC, Neale CMU (1989) Spectral inputs improve corn crop coefficients and irrigation scheduling. Trans ASAE 32(6):1901–1908

Brown PW (1989) Accessing the Arizona Meteorological Network (AZMET) by computer. (Ext rep 8733) The University of Arizona, Tucson

Brown PW (1991) Normal values of heat unit accumulation for southern Arizona. (Ext rep 190041) The University of Arizona, Tucson

Choudhury BJ, Amhed NU, Idso SB, Reginato RJ, Daughtry CS (1994) Relations between evaporation coefficients and vegetation indices studied by model simulations. Remote Sensing Environ 50:1–17

Colaizzi PD, Barnes EM, Clarke TR, Choi CY, Waller PM (2003) Estimating soil moisture under low frequency surface irrigation using the CWSI. J Irrig Drain Eng 129:27–35

Doorenbos J, Pruitt WO (1977) Crop water requirements. (FAO irrigation and drainage paper 24) Food and Agricultural Organization of the United Nations, Rome

Heilman JL, Heilman WE, Moore DG (1982) Evaluating the crop coefficient using spectral reflectance. Agron J 74:967–971

Hendrey GR, Kimball BA (1994) The FACE program. Agric For Meteorol 70:3–14

Howell TA, Evett SR, Tolk JA, Schneider AD (2002) Evapotranspiration of full-, deficit-irrigated and dryland cotton on the Northern Texas high plains. In: Burt CM, Anderson SS (eds) Energy, climate, environment, and water: Proceedings of the US committee on irrigation and drainage/EWRI conference, 9–12 July, San Luis Obispo, California. USCID, Denver, Colo., pp 321–329

Hunsaker DJ (1999) Basal crop coefficients and water use for early maturity cotton. Trans ASAE 42(4):927–936

Hunsaker DJ, Hendrey GR, Kimball BA, Lewin KF, Mauney JR, Nagy J (1994) Cotton evapotranspiration under field conditions with CO_2 enrichment and variable soil moisture regimes. Agric For Meteorol 70:247–258

Hunsaker DJ, Pinter PJ Jr, Cai H (2003) Alfalfa basal crop coefficients for FAO-56 procedures in the desert southwestern US. Trans ASAE 45(6):1799–1815

Jackson RD, Huete AR (1992) Interpreting vegetation indices. Prev Vet Med 11:185–200

Jackson RD, Idso SB, Reginato RJ, Pinter PJ Jr (1980) Remotely sensed crop temperatures and reflectances as inputs to irrigation scheduling. In: Irrigation and drainage special conference proceedings, 23–25 July, Boise, Idaho. ASCE, New York, pp 390–397

Jensen ME, Allen RG (2000) Evolution of practical ET estimating methods. In: Evans RG, Benham BL, Trooien TP (eds) Proceedings of the 4th decennial national irrigation symposium, 14–16 Nov 2000, Phoenix, Arizona. ASAE, St Joseph, Mich., pp 52–65

Jensen ME, Burman RD, Allen RG (1990) Evapotranspiration and irrigation water requirements. (Manuals and reports on engineering practices no. 70) ASCE, New York

Mauney JR, Kimball BA, Pinter PJ Jr, LaMorte RL, Lewin KF, Nagy J, Hendrey GR (1994) Growth and yield of cotton in response to a free-air carbon dioxide enrichment (FACE) environment. Agric For Meteorol 70:31–48

Moran MS, Mass SJ, Pinter PJ Jr (1995) Combining remote sensing and modeling for estimating surface evaporation and biomass production. Remote Sensing Rev 12:335–353

Neale CMU, Bausch WC, Heerman DF (1989) Development of reflectance-based crop coefficients for corn. Trans ASAE 32(6):1891–1899

Pinter PJ Jr, Kimball BA, Mauney JR, Hendrey GR, Lewin KF, Nagy J (1994) Effects of free-air carbon dioxide enrichment on PAR absorption and conversion efficiency by cotton. Agric For Meteorol 70:209–230

Pinter PJ Jr, Kimball BA, Garcia RL, Wall GW, Hunsaker DJ, LaMorte RL (1996) Free-air CO_2 enrichment: responses of cotton and wheat crops. In: Koch GW, Mooney HA (eds) Terrestrial ecosystems: responses to elevated carbon dioxide. Academic Press, Orlando, Fla., pp 215–249

Slack DC, Martin EC, Sheta AE, Fox F Jr, Clark LJ, Ashley RO (1996) Crop coefficients normalized for climatic variability with growing-degree-days. In: Camp CR, Sadler EJ, Yoder RE (eds) Evapotranspiration and irrigation scheduling: Proceedings of an international conference, 3–6 November 1996, San Antonio, Texas. ASAE, St Joseph, Mich., pp 892–898

Stegman EC (1988) Corn crop curve comparison for the Central and Northern Plains of the US. Appl Eng Agric 4(3):226–233

Tolk JA, Howell TA (2001) Measured and simulated evapotranspiration of grain sorghum grown with full and limited irrigation in three high plains soils. Trans ASAE 44(6): 1553–1558